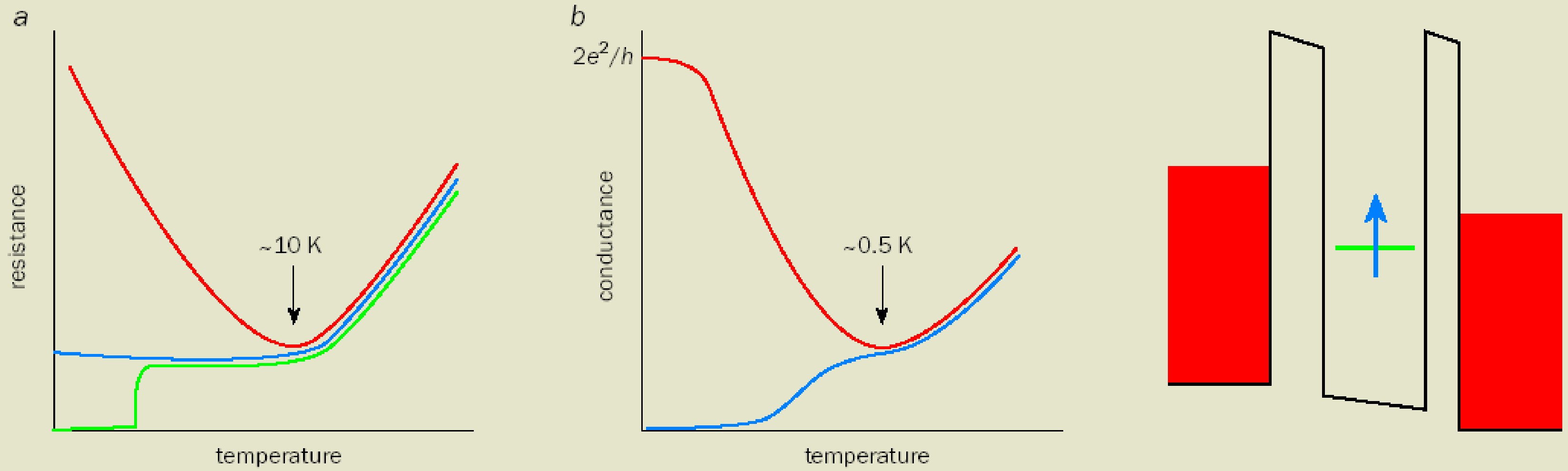
J. Kondo

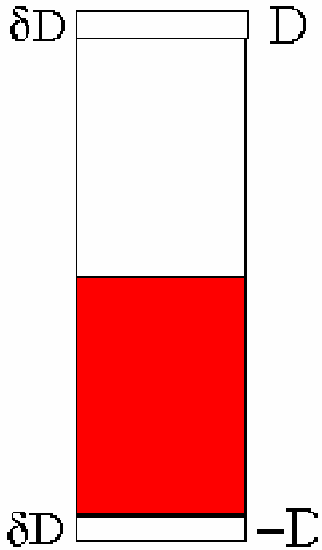
## 1 The Kondo effect in metals and in quantum dots




(*a*) As the temperature of a metal is lowered, its resistance decreases until it saturates at some residual value (blue). Some metals become superconducting at a critical temperature (green). However, in metals that contain a small fraction of magnetic impurities, such as cobalt-in-copper systems, the resistance increases at low temperatures due to the Kondo effect (red). (*b*) A system that has a localized spin embedded between metal leads can be created artificially in a semiconductor quantum-dot device containing a controllable number of electrons. If the number of electrons confined in the dot is odd, then the conductance measured between the two leads increases due to the Kondo effect at low temperature (red). In contrast, the Kondo effect does not occur when the dot contains an even number of electrons and the total spin adds up to zero. In this case, the conductance continuously decreases with temperature (blue).

# IR divergence

$$T_{k\uparrow,k'\uparrow} = JS_Z\left(1+2J\nu_0 Log(D/T)+\ldots\right)$$

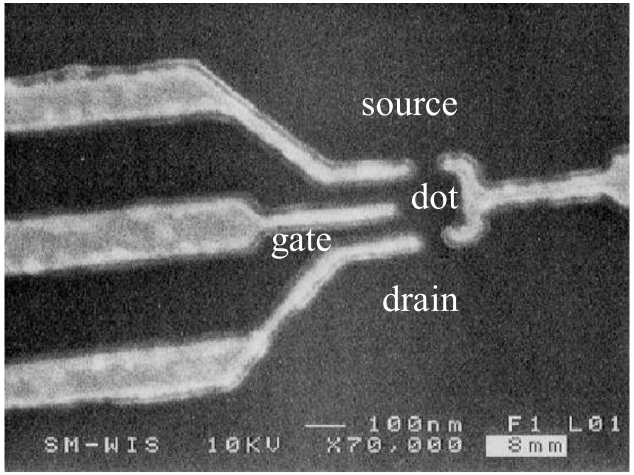



- Surprising result obtained by J. Kondo (1964).
- Perturbation breaks down at low energy.
- Led to renormalization group ideas (Wilson), new fixed point (ground state) at low energy.
- Energy scale generated by renormalization: Kondo temperature.

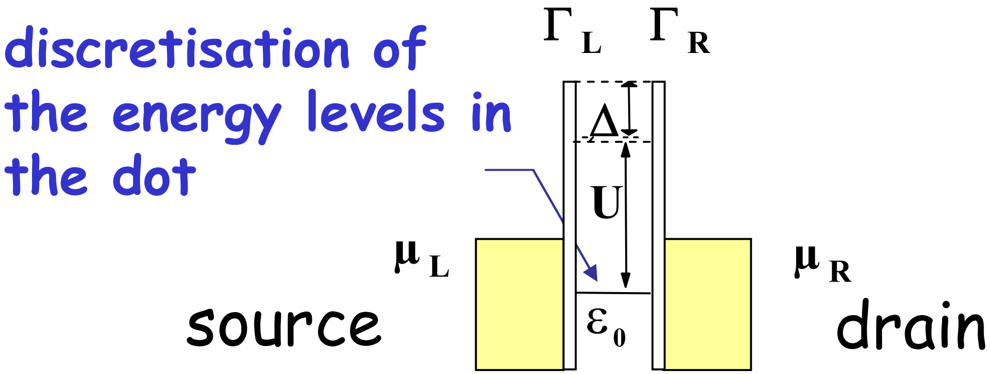
$$T_K = D\,e^{-1/2\nu J}$$

# Quantum dots

## experimental device




## model



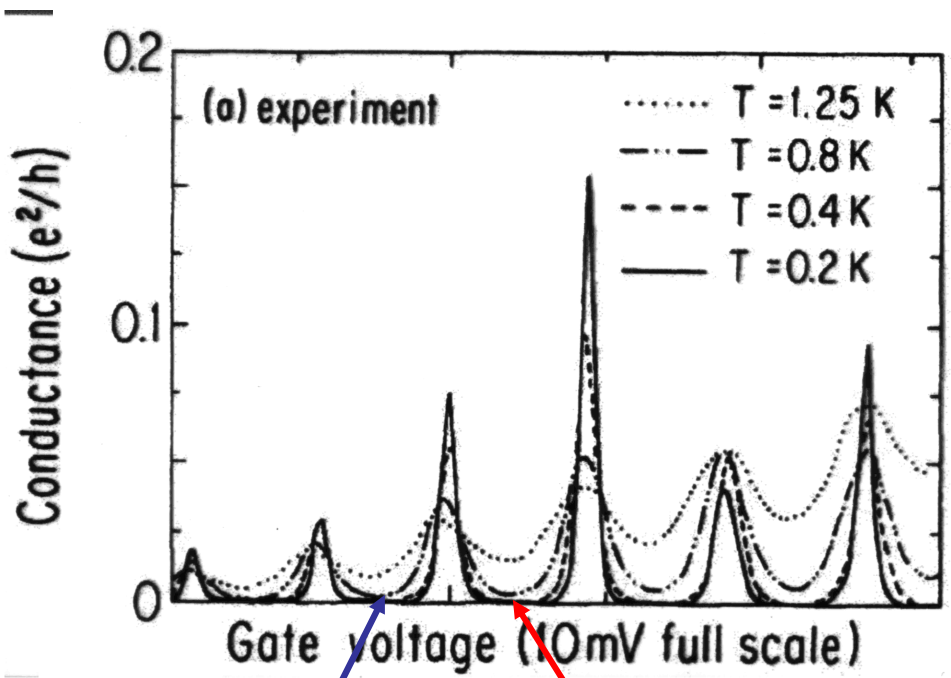

charge energy $e^2/2C$ $\leftrightarrow$ Coulomb energy $U$

gate voltage $V_G$ $\leftrightarrow$ energy $\varepsilon_0$

lateral gate voltages $V_{GL}$ and $V_{GR}$ $\leftrightarrow$ tunnel energies $\Gamma_L$ and $\Gamma_R$

source-drain voltage $\leftrightarrow$ $\mu_L - \mu_R$

# Coulomb blockade



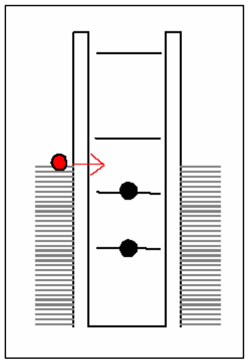

$$\Gamma << k_B T << \Delta << U$$

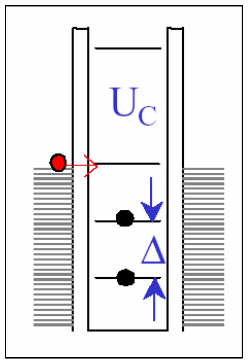
- quantization of the electronic transfer through the dot
- effect of temperature

'even' valleys
N

'odd' valleys
N+1

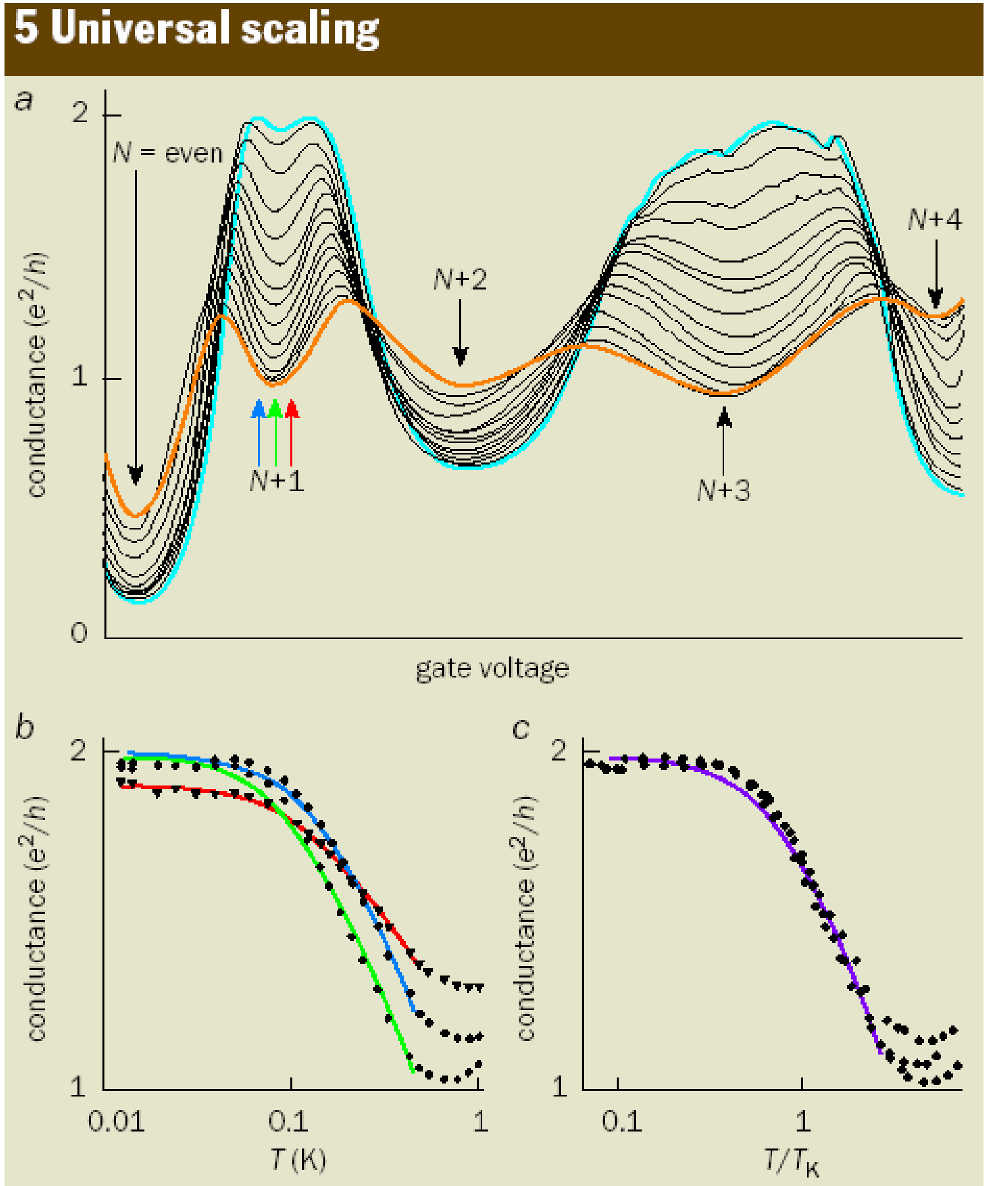
OFF






ON

state with
N electrons

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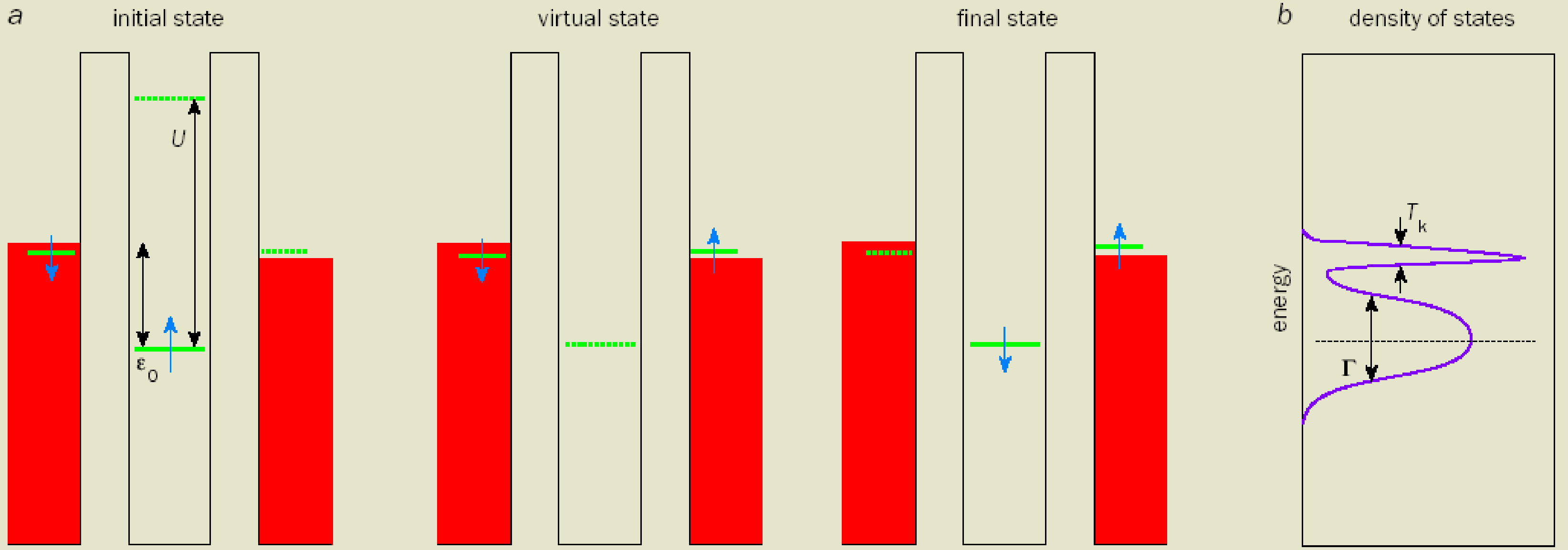
## 2 Spin flips




($a$) The Anderson model of a magnetic impurity assumes that it has just one electron level with energy $\varepsilon_0$ below the Fermi energy of the metal (red). This level is occupied by one spin-up electron (blue). Adding another electron is prohibited by the Coulomb energy, $U$, while it would cost at least $|\varepsilon_0|$ to remove the electron. Being a quantum particle, the spin-up electron may tunnel out of the impurity site to briefly occupy a classically forbidden "virtual state" outside the impurity, and then be replaced by an electron from the metal. This can effectively "flip" the spin of the impurity. ($b$) Many such events combine to produce the Kondo effect, which leads to the appearance of an extra resonance at the Fermi energy. Since transport properties, such as conductance, are determined by electrons with energies close to the Fermi level, the extra resonance can dramatically change the conductance.